

# Two-dimensional refractive index profiling of optical fibers by modified refractive near-field technique

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## ABSTRACT

The refractive index distribution in the core-cladding region of an optical fiber plays an important role in determining the transmission and dispersion properties of the waveguide. The refracted near-field technique (RNF) is among the most widespread techniques used for measuring the refractive index profile of optical fibers and is based on illuminating the end-facet of a fiber with a focused beam whose vertex angle greatly exceeds the acceptance angle of the fiber, which is immersed in an index matching liquid. What one observes are then the refracted unguided rays rather than the guided rays. Nevertheless, the standard refracted near-field technique cannot be applied to a wide range of optical fibers e.g. if their shapes are not axially symmetric. In this work we demonstrate a modified method which allows 2-D imaging of the refractive index profile and thereby overcoming the axial symmetric limitation of the standard RNF. The new system is operating at 630 nm and based on the same principle of the RNF, but the optical path is reversed so that the light at the fiber end-facet is collected by an objective lens and detected by a CCD camera. The method does not require scanning over the fiber end-facet. Thus the system is faster and less sensitive to vibrations and external conditions compared to the standard RNF, furthermore it allows averaging to improve the signal to noise ratio. The spatial resolution of the system is determined by the numerical aperture of the objective and by the resolution of the CCD camera. To calibrate the setup, a reference multi-step index fiber provided by National Physical Laboratory was used.

**Keywords:** Refracted near-field technique, refractive index profile

## 1. INTRODUCTION

The main characteristics of optical waveguides are given by the distribution of the refractive index profile. Parameters such as band-width, spot size, single-mode propagation conditions, and waveguide coupling coefficients are all depending on the refractive index profile. Knowledge of the refractive index profiles is very crucial, not only for the theoretical prediction of the waveguide characteristics, but also for controlling the fabrication process used to produce optical fibers. Thus, it is very important from the practical and theoretical point of view to establish a fast, efficient and accurate method for measuring the refractive-index profile of optical waveguides. The profile measurement, however, is very demanding due to the small guiding structure of the fiber and the low refractive-index difference.

Since the development of index guided optical fibers, a large bunch of methods have been introduced to measure the refractive index profile of optical fibers and waveguides [1],[2] such as the microscopic method, the reflection method, the focusing method, the transverse interferometry, the near-field technique and the refracted near-field technique. One of the most promising techniques for simple and high-resolution measurements is the refracted near-field technique (RNF). First proposed and demonstrated by Stewart [3], the method was further developed by White [4] and analyzed by Young [5]. The technique is attractive since it is straightforward and gives directly the refractive index variation across the entire fiber. Furthermore it can be applied to fibers with any length and there is no correction for leaky modes required as in the transmitted near-field technique. Additionally, this method is relatively insensitive to the presence of contamination at the fiber's end facet surface compared to the reflection methods, and apart from a good cleave and clean end-facet no special fiber preparation is needed, as it is for many interference techniques. Nevertheless, to obtain a refractive index profile by using the refracted near-field technique, the fiber end-facet has to be scanned, since the refracted near-field technique is a non-imaging technique. Scanning all of the fiber end-facet would be very time consuming, thus only a line scan is usually used for the refracted near-field technique, which results in a substantial reduction of the expenditure of time. Furthermore the line scan restricts the fiber geometry to an axially symmetric geometry, this is the reason why normally PM or

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microstructured fibers cannot be analyzed with this technique. In this paper we give an overview on the refracted near field technique and we describe our modification of the standard technique which results in a very fast, simple and repeatable apparatus which allows 2-D imaging (one picture, so no scanning is required) of the refractive index profile and thereby overcoming the axial symmetric limitation of the standard RNF. A similar system had been proposed in [6],[7] but it relied on circular symmetry of the fiber structure. The new system can be applied on optical fibers of any geometry and microstructure to obtain their refractive index profiles.

## 2. PROCEDURE DESCRIPTION

The measurement principle and setup of the standard refracted near field technique is previously described in details [5],[8],[9]. The principle of the method is comparatively simple and it can be explained using Fig. 1. A radially symmetric fiber is placed in a transparent movable cell which is containing a liquid whose index of refraction is almost matched (slightly higher than) that of the fiber cladding. The fiber end-facet is illuminated by a focused beam whose numerical aperture greatly exceeds the acceptance angle of the fiber. The most extreme rays of the incident cone (see Fig. 1: all ray with a large angle than  $\beta_1$ ) are therefore not guided by the fiber, rather than being refracted and emerged from the exit face of the cell. If the refractive index of the fiber at the point of illumination is changed, by e.g. a line scan across the end-facet of a graded-index fiber, then the vertex angle of the emerging cone will change slightly. An important element is the opaque circular stop, which is introduced behind the fiber at the exit face of the cell and designed to block the guided light and the leaky modes from the fiber. This results in a hollow cone of rays that is transmitted beyond the stop. As the fiber is scanned, the inner radius of this cone is always equal to the radius of the introduced opaque stop. However, the outer radius of the hollow cone varies with the refractive index of the fiber at the point of incidence of the scan. Therefore, the power that is transmitted around the opaque circular stop also varies with index of refraction at the point of illumination. In Fig. 1 the ray in the incident cone of light having an angle of incidence  $\theta_1$  is incident on the fiber at that location where the index of refraction is  $n(r)$ . This ray is refracted out of the cell at the angle of refraction  $\theta_3$  depending up on the refractive index at the point of incident. Using Snell's law at the exit and entry from the cell ( $n_L$  is the refractive index of the liquid in the cell) one can get the well-known fundamental equation for the refracted near field profiling derived by White [4].

$$n^2(r) = \sin^2\theta_1 + n_L^2 - \sin^2\theta_3 \quad (1)$$

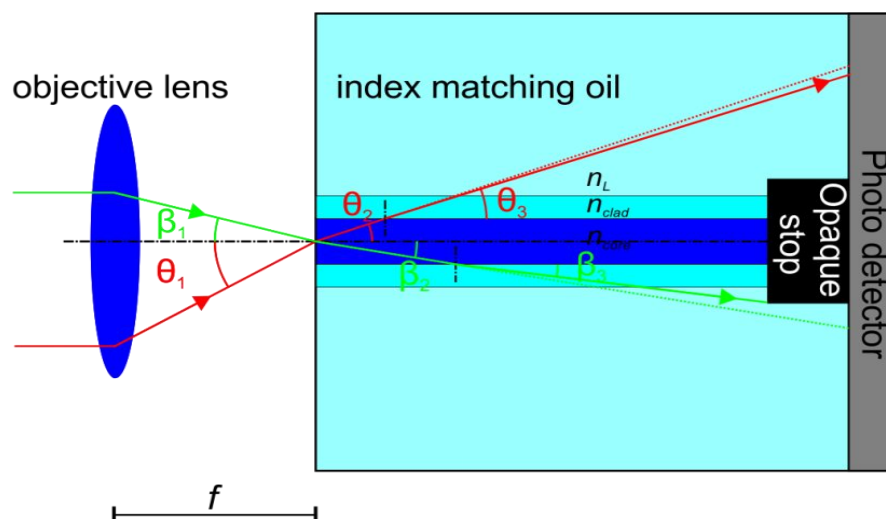


Figure 1. Schematic diagram to explain the refracted near field technique.  $\theta_1$  represents the angle of incidence of the focused cone into the fiber, and  $\theta_3$  represents the angle of incidence of the emergent cone.

Assuming that we have a Lambertian light source where the power per solid angle is constant in the beam, the power transmitted around the stop into the detector  $P(\theta_1)$  can be expressed as

$$P(\theta_1) = A(\sin^2\theta_3 - \sin^2\theta_s) \quad (2)$$

Where  $\theta_s$  is the angle subtended by the stop, and A is the constant of proportionality [5]. Now as the focused cone is scanned along the fiber, the refractive index at the point of illumination changes and consequently the vertex angle of the emerging cone varies which in turn modifies the power transmitted around the stop  $P(\theta_1)$ . Using equation (1) and (2), White shows that the power transmitted around the stop should vary linearly with the refractive index of the fiber at the point of illumination:

$$P(\theta_1) \cong K_1 - K_2 n(r) \quad (3)$$

where  $K_1$  and  $K_2$  are constants.

Thus the heart of the refracted near field technique lies in the fact that, under the right conditions such as having a Lambertian source, the change of transmitted power is precisely proportional to the change of refractive index of the fiber at the point of illumination. However, Young showed in his analysis that if the source is not Lambertian, the transmitted power may still be sufficiently linear over a small range of angles and indices [5].

The new system is based on the same principle of the refracted near field technique but now the optical path is inverted. The new scheme of the system is represented in Fig 2. An LED lamp operating at 630 nm is illuminating a cell containing Limonene oil whose index of refraction is almost matched to (slightly higher than) the fiber cladding. An optical diffuser is used just right before the Limonene cell to achieve a homogenous light distribution in the cell. As shown in Fig. 2, the fiber entrance end-facet is blocked using a mask to avoid the guidance of light by the fiber, so that only rays with a larger angle than the acceptance angle of the fiber remain. The refracted light at the end-facet of the fiber is collected using an objective lens and a CCD camera. Since the refractive index of the core is higher than the cladding, the remaining rays are refracted out of the core into the cladding, resulting in intensity distribution with a lower intensity in the core than in the cladding.

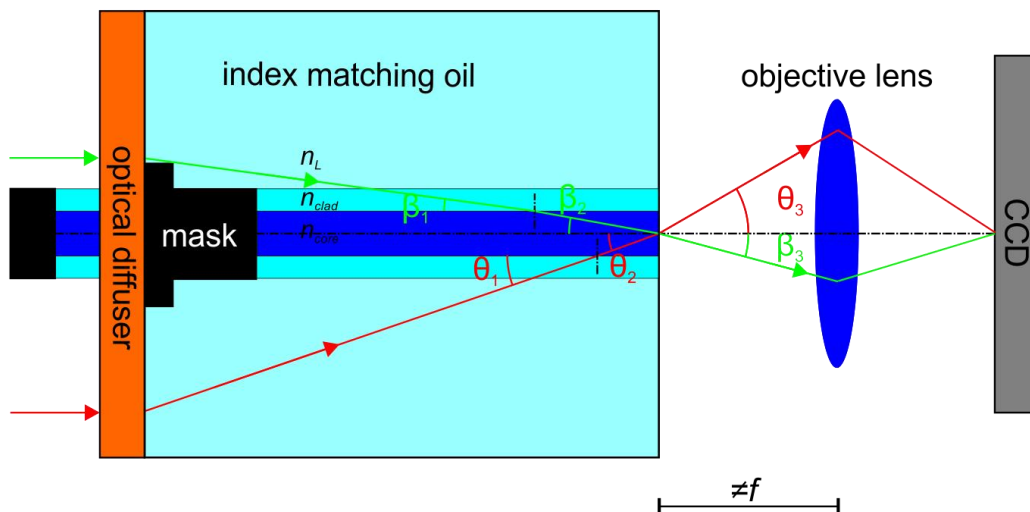


Figure 2. Schematic diagram of the modified refracted near field technique, and what we call the inversed refracted near technique since the operation principle of the new system is the same as in the standard refracted near field technique but the optical path is inversed, and a CCD camera is used instead of photo detector.

### 3. MEASUREMENTS

#### Calibration and linearity

Before measuring the refractive index profiles of various optical fibers, the system has to be tested and calibrated. Several methods have been used to calibrate the system. White translated the opaque stop in the direction parallel to the fiber axis, and then he calculated the power transmitted around the opaque stop as a function of position and thereby he related the transmitted power to the index of refraction. Young used four different oils with known index of refraction sequentially with each of three quartz-fiber samples [10]. However, we looked for a method that is fast, more direct and more amenable to analysis as a measurement system. Therefore we used for the calibration a multi-step index optical fiber provided by the National Physical Laboratory (NPL), Teddington, UK. The refractive index values provided by NPL are used for the calibration.

Fig. 3 shows the image of the multi-step index optical fiber end-facet. The four refractive index values provided by NPL were used to calibrate the device by the four intensity levels recorded by the CCD.

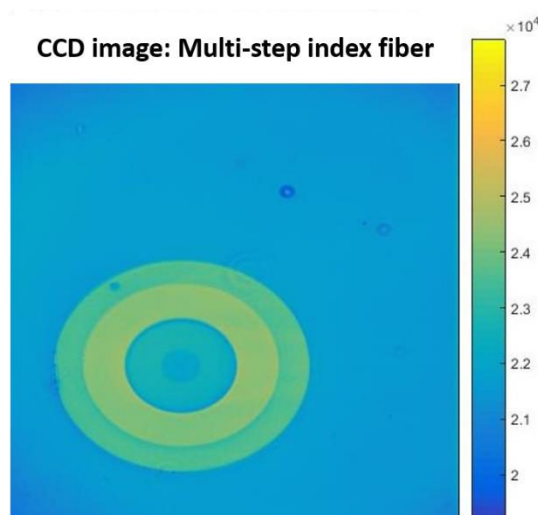


Figure 3. 2-D image of the reference multi-step index fiber. The image shows different intensity levels along the fiber cross section. The intensity variations correspond to the 4 refractive index steps.

The image recorded by the CCD camera is saved as 16 bit file, and then it is uploaded and processed by Matlab. The intensity of the light collected from the fiber end is represented by the gray scale of the image which varies between 0 (black) and  $2^{16}$  (white). By assuming that the refractive index is in a linear relationship with the light intensity represented by the grey scale, the refractive index profile is obtained. The calibration points were linearly fitted using the least square method and are shown in Fig. 4.

The calculations showed linearity at the 95 % confidence level. After the calibration, the 2-D refractive index profile of the fiber was computed and it is shown in Fig. 5. By positioning an arbitrarily line vector along the fiber cross-section, they gray level information along the desired vector is evaluated and the 1-D index profile is obtained. Fig. 6 shows the 1-D index profile over the cross section of the reference multi-step index fiber. Our measurements showed a good agreement with the NPL indices. The indices given by the NPL were measured using the standard refracted near field technique with a claimed uncertainty of  $\pm 0.00015$ . Table 1 shows both the indices from the NPL and the measured ones by our system. In addition, the linearity of the electronics has been verified by measuring the index difference at different exposure time.

The sharp peak between the different interfaces and especially between interfaces 2 and 3 are still under investigation (see Fig. 6). These peaks appears only in the measurement of the calibration multi-step index fiber, and don't appear in the measurements of other optical fibers. Nevertheless, these peaks can be ignored and they don't affect the calibration of the device.

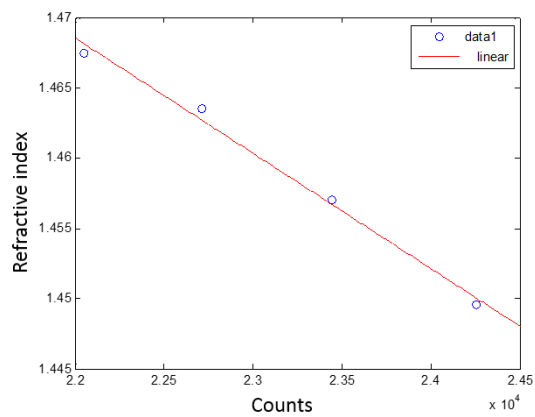


Figure 4. The calibration curve obtained from the reference multi-step index fiber. The horizontal axis is the recorded intensity and the vertical axis is the four refractive index steps provided by NPL at 633 nm. The calibration points were linearly fitted using the least square method.

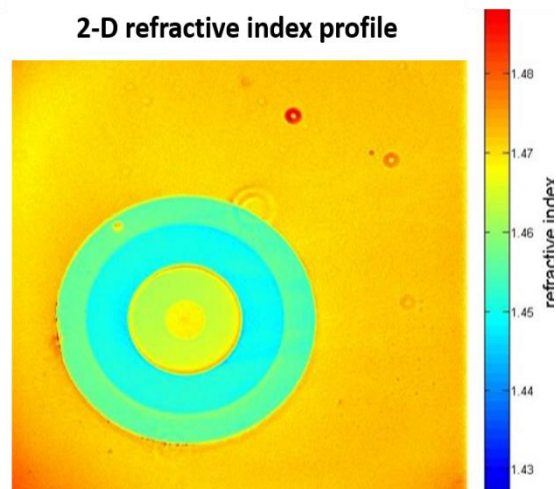


Figure 5. 2-D refractive index profile of the reference multi-step index fiber.

Table 1. The refractive indices difference of the multi-step index fiber obtained by NPL and by the modified refracted near field system

	NPL values	Modified RNF system
Level 4-2	$0.01785 \pm 0.00015$	$0.017966 \pm 0.00054$
Level 3-2	$0.01395 \pm 0.00015$	$0.013852 \pm 0.00073$
Level 4-3	$0.00390 \pm 0.00005$	$0.004135 \pm 0.00053$
Level 2-1	$-0.00740 \pm 0.00010$	$-0.006972 \pm 0.00061$

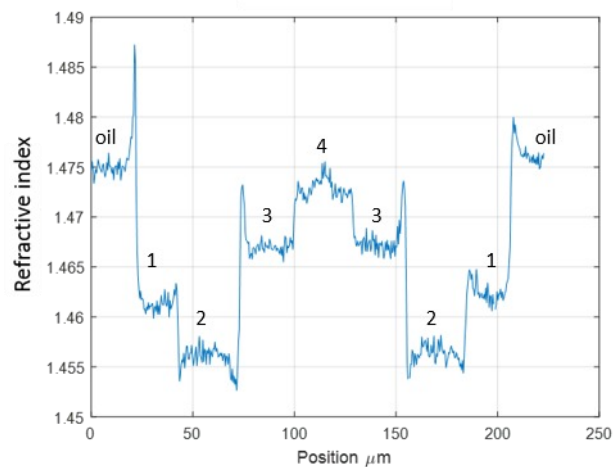


Figure 6. 1-D refractive index profile of the reference multi-step index fiber.

### Refractive index profiles of optical fibers

#### A) Single-core step-index fiber:

After calibrating the system, the 2-D and 1-D refractive index profiles of optical fibers were recorded and computed. Fig. 7 and Fig. 8 show the 2-D and the 1-D refractive index profiles of a single mode step index fiber respectively.

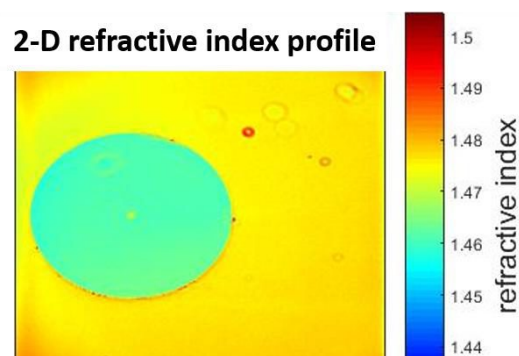


Figure 7. 2-D refractive index profile of single mode step index fiber

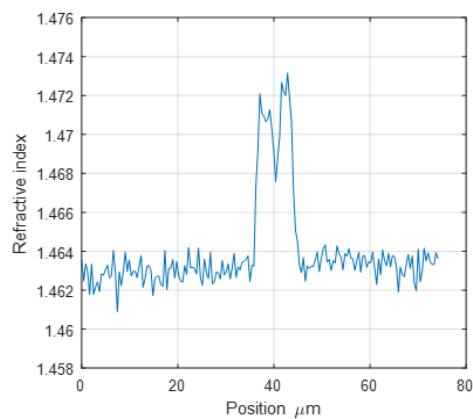


Figure 8. 1-D refractive index profile of single mode step index fiber

We obtained an index step of  $0.00676 \pm 0.00051$ . The index step is in an agreement with the estimated one obtained from the numerical aperture of the fiber. The measurement shows clearly the well-known refractive index dip at the very center of the core (see Fig. 8). This central index depression is an artifact primarily of the high temperature used in the collapse steps of the MCVD process.

#### B) Multi-core step-index fiber

Fig. 9 and Fig. 10 show the 2-D and the 1-D refractive index profile of a multi-core fiber respectively.

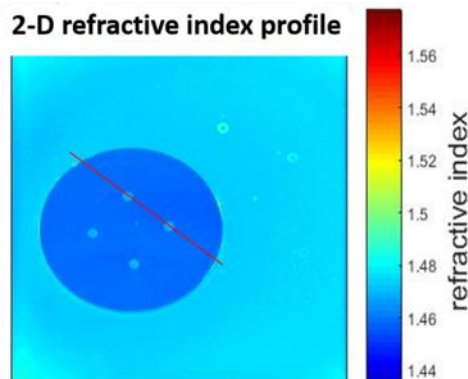


Figure 9. 2-D refractive index profile of a multi-core fiber with 4 cores. The line vector (in red) is used to obtain the 1-D refractive index profile along the desired cross section.

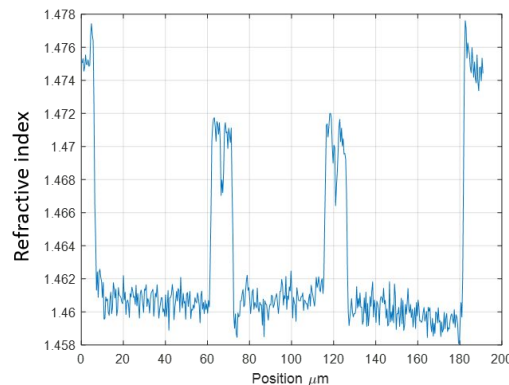


Figure 10. 1-D refractive index profile of a multi-core fiber.

The 1-D refractive index profile was obtained by positioning an arbitrary line passing through 2 cores along the fiber's cross section (see Fig. 9). An index step of  $0.010391 \pm 0.00064195$  was determined. The refractive index step was verified by a measurement done with a reflection based index profiling. The central index depression of the cores of this fiber are resolved by our device (see Fig. 10).

## 4. CONCLUSION

Refractive index profiling and geometry characterization of optical fibers have been obtained by a modification of the standard refracted near field technique. Our modification resulted in a system that doesn't require scanning over the fiber end-facet. Therefore limitations due to none axially symmetrical optical fibers have been overcome by obtaining a 2-D index profile. Thus our device is faster and less sensitive to vibrations and external conditions compared to the standard refracted near field technique. The estimated accuracy of the system is similar to that obtained for optical fibers which is approximately  $6 \times 10^{-4}$ .

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